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Review of Ultra High-Gradient Acceleration Schemes, Results of Experiments

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A dramatic improvement in energy gain per unit cost is mandatory for the future of very high energy accelerators, for which RF-acceleration would be replaced by new tech-niques. Several schemes have been proposed (laser driven, beam driven accelerators) and tested. A critical review of these schemes and experimental results is presented, with considerations on the most promising techniques and the effort still needed. Important parameters for high luminosity (efficiency, emittance preservation, ...) are discussed.

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REVIEW OF ULTRA HIGH-GRADIENT ACCELERATION SCHEMES, RESULTS OF EXPERIMENTS

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Abstract

A dramatic improvement in energy gain per unit cost is mandatory for the future of very high energy accelerators, for which RF-acceleration would be replaced by new techniques. Several schemes have been proposed (laser driven, beam driven accelerators) and tested. A critical review of these schemes and experimental results is presented, with considerations on the most promising techniques and the effort still needed. Important parameters for high luminosity (efficiency, emittance preservation, ...) are discussed.

1 INTRODUCTION

For more than three decades the collision energy in particle colliders has increased exponentially in time. This remarkable success of the accelerator field is described by the so-called Livingston curve. A recent version of the Livingston curve is shown in Fig. 1. It includes past colliders, the future LHC and a possible next-generation e^+e^- linear collider at 0.5 TeV. It is seen that up to 1995 the accelerators followed the Livingston curve. The rapid increase in available collision energy provided a thriving particle physics community with multiple experimental opportunities.

This success story of high energy colliders seems now to have slowed down. Though future machines significantly extend the available energy reach in particle physics, they arrive late, such that they fall below the Livingston curve. In addition, fewer projects are built in a given time period. This situation was recently discussed by M. Tigner [1] who opened the question whether accelerator-based particle physics does have a future. The signs of saturation in collision energy indicate that practical limits are being approached for high energy colliders.

The most important practical limitation that high energy colliders face today is the cost per GeV of beam energy. The goal of high energy accelerator research is a low-cost technology and accelerator design that provides many more GeV per cost unit. In this paper we review technologies for ultra-high gradient acceleration of charged particles, ranging from meter-long plasma-based acceleration to the mm-size laser-driven "accelerator on a chip". These new technologies promise gradients from several 100 MV/m up to 150 GV/m and would allow for ultra-compact linear colliders in the many TeV range.

2 GENERAL CONCEPTS

The field of advanced accelerator research originates in the famous 1979 paper of Tajima and Dawson [2]. Over the last 23 years it has expanded into an active and diverse research discipline with many different ideas and concepts being considered. It is not the purpose of this paper to give a complete and fair description of all present activities. The interested reader is directed towards the proceedings of the Workshops on Advanced Accelerator Concepts (e.g. [3]) and some recent overview papers [4, 5, 6]. A few selected directions, that appear most promising at this time, are discussed here.

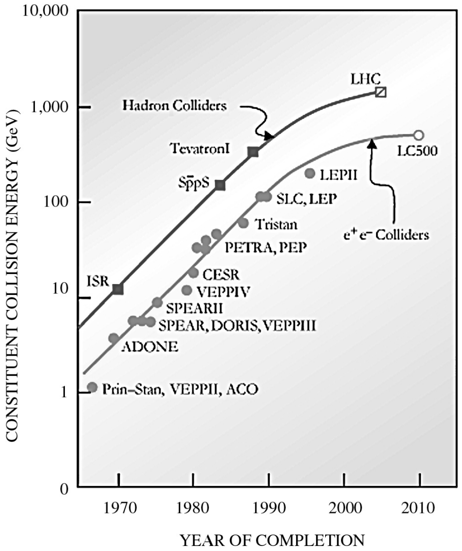

Figure 1: The Livingston curve showing constituent collision energy for different accelerators versus year of completion. From [1]. [Courtesy M. Tigner, Cornell]

Acceleration in plasma Plasma based accelerators replace the metallic walls of conventional RF structures with a plasma. The damage problems faced in high-gradient metallic structures [7, 8] are therefore not an issue. Laser beams (laser wakefield accelerator LWFA) or charged particle beams (plasma wakefield accelerator PWFA) are used to excite space-charge oscillations in the plasma. The resulting longitudinal fields can be used for particle acceleration. Accelerating gradients of up to 160 GV/m have been demonstrated in experiments [9] and plasma structures have been built from the mm to the meter scale [10]. Plasma-based concepts presently offer the highest gradient acceleration and will be discussed in detail in the later part of this paper.

Acceleration in vacuum Acceleration in vacuum uses metallic or dielectric structures to couple a power source (laser fields or beam induced wakefields) to the particle beam. Accelerating fields tend to be smaller than in the plasma-based concepts, however, the stability problems of plasmas are avoided.

The idea of an ”accelerator on a chip” with dielectric structures, as envisioned by Barnes et al, seems intriguing: ”The goal is to lithographically produce the power source, power transmission system, accelerator structures and beam diagnostics on a single substrate by semiconductor process.” [11] The use of a laser with micron wavelength as power source implies accelerating structures with mm dimensions. The high available peak power and high available wall-plug-to-photon efficiencies (20-40%) of modern solid-state lasers [11] are encouraging. The arrangement of these microstructures in accelerator arrays could optimize efficiency and available beam current. A SLAC experiment E-163 will further address this concept of laser acceleration in vacuum, aiming at an accelerating gradient of 0.3 GV/m. It is noted that the ongoing LEAP experiment [12] has seen ”only tantalizing hints of the interaction signature” [11], citing jitter problems for position and timing of laser and particle beams. These problems should be alleviated with the ongoing progress in laser control, as recently demonstrated by achieving submicroradian laser pointing stability [13].

Dielectric wakefield accelerators also employ dielectric structures and use a drive beam to excite an accelerating wakefield, either in a collinear or two-beam scheme. Gradients are envisaged to be in the 0.1-1 GV/m range.

Inverse Free Electron Lasers (IFEL) have been used at the STELLA staging experiment to produce 1 μm long micro-bunches and to accelerate these bunches by 6 MeV/m [14]. This important experiment demonstrated femto-second accuracy in the laser-beam synchronization. The acceleration goal for future experiments is 90 MeV/m. Due to synchrotron radiation, the use of IFEL’s is limited to beam energies below 200 GeV [4] and would therefore be restricted to the low energy part of the accelerator.

3 BASIC PLASMA FEATURES

The following discussion is focused on plasma-based acceleration which promises the highest accelerating gradients. The basic features of plasma based concepts are discussed. These concepts rely on three important steps. First, a plasma channel must be generated, for example by sending an ionizing laser through a neutral gas. Secondly, space charge oscillations are induced in the plasma channel, either with a driving particle bunch (PWFA) or with a laser pulse (LWFA). There exist several basic concepts for laser plasma accelerators: single short pulse of photons, a series of pulses with two different frequencies, and a self-modulated laser pulse (Raman forward scattering instability). Third, a witness beam is injected with the right phase and collinear with respect to the longitudinal plasma wakefield.

For the case of an electron beam driver and for a beam density larger than the plasma density the principle is easily understood (see also illustration in Fig. 2):

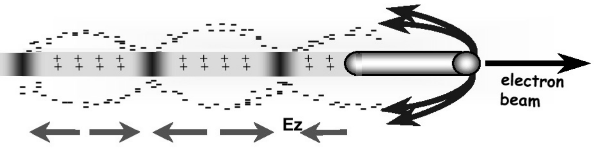

Figure 2: Principle of beam-driven plasma wakefield acceleration. [Courtesy T. Katsouleas, USC]

1. The electron bunch enters the homogeneous plasma and plasma electrons are expelled from the beam region. The plasma ions are less mobile.
2. After some fraction of the bunch length all plasma electrons in the beam area have been expelled (blowout regime) and the rest of the electron bunch experience a uniform focusing field in the ion channel.
3. After passage of the electron bunch the plasma electrons rush back towards the trajectory of the beam and overshoot. A plasma space charge oscillation starts.
4. The space charge modulation results in longitudinal fields that can accelerate particles injected with the right phase.

The properties of plasma wakefield acceleration depend strongly on the plasma density n_0. For wakefields induced by a drive beam some approximations can be made. The wavelength λ_p of the accelerating plasma wakefield can be estimated from:

$$\lambda_p \approx \sqrt{\frac{10^{15}\mathrm{cm}^{-3}}{n_0}}\ \mathrm{mm} \tag{1}$$

If the length σ_z and population N_b of the driving electron bunch fulfills $N_b r_e/\sigma_z \approx 1$ then the longitudinal field gradient W_z can be approximated from:

$$W_z \approx 100\sqrt{n_0}\ \ \mathrm{V/m} \tag{2}$$

For an arbitrary bunch length it is expected that W_z scales as N_b/σ_z^2. The pure ion column acts as a strong focusing lens on an injected electron bunch. The transverse focusing gradient W_r/r is given by:

$$\frac{W_r}{r} \approx 960\pi\left(\frac{n_0}{10^{14}\mathrm{cm}^{-3}}\right)\ \mathrm{T/m} \tag{3}$$

For a plasma density $n_0 = 10^{14}$ cm^{-3} these formulae give a plasma wavelength of 3.3 mm, an accelerating field of 1 GV/m, and a transverse focusing gradient of about 3000 T/m. These are very crude estimates and sophisticated simulation programs are being used to predict these parameters with excellent accuracy. However, the simple relationships illustrate the basic properties of plasma accelerators: Short wavelength, high accelerating fields, and strong transverse focusing fields. The important consequences of these basic features for the progress of experimental studies will be discussed later.

4 EXPERIMENTAL RESULTS

The studies on plasma accelerators can be divided into laser-driven and beam-driven experiments. While laser-driven plasma wakefield acceleration has achieved the highest accelerating gradients at high plasma densities, it has been technically limited to mm lengths. On the other side beam-driven experiments with lower plasma densities have achieved lower gradients, but allowed studying beam-plasma interaction for lengths of up to 1.4 m.

Laser induced wakefields There exists a large number of experimental results on laser-induced plasma wakefield acceleration. A few key results, that were achieved with a self-modulated short laser pulse [15] in dense plasmas, are quoted:

- 1995: 30 GV/m over 0.6 mm [16].
- 1997: $>$ 100 GV/m over $<$1 mm [17].
- 1998: 160 GV/m over 0.6 mm [9].
- 1999: $>$ 100 GV/m over $<$1 mm [18].

Ultra-high accelerating gradients were consistently observed in different European, American, and Asian laboratories. The good reproducibility of the results leaves no doubt that the high gradient plasma wakefields do exist and do indeed accelerate particles. The experimental data for a selected measurement [17] are shown in Fig. 3. Highly accelerated electrons have indeed be measured. However, as in this scheme plasma electrons are captured and accelerated, the obtained beam has a large energy spread with only very few electrons at the highest energies. This method has the inherent advantage that an injected electron beam is not required. Studies can be done without large investments into a beam infrastructure.

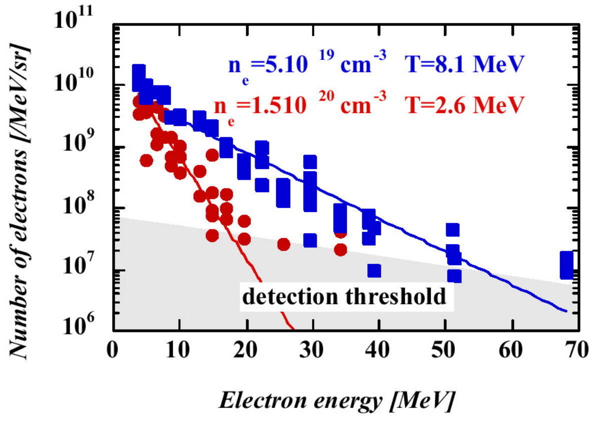

Figure 3: Number of electrons per energy bin and per steradian versus particle energy (laser-induced plasma wakefield acceleration over about 1 mm) [17]. Two different plasma densities are compared with less particles captured for shorter wavelength. [Courtesy F. Amiranoff, LULI]

The self-modulated laser wakefield acceleration scheme relies on an instability and is therefore not suited for a high energy accelerator. An alternative set-up seems much more adequate for the needs of high energy colliders: a plasma wakefield is induced with a single laser pulse and an injected electron bunch is accelerated. This scheme was tested successfully for a length of about 1 mm and an accelerating gradient of 1.5 GV/m has been demonstrated [19].

The laser schemes are limited in practice on one side by the availability of injected particle bunches with small emittance and short length and on the other side by the diffraction length of the laser beam. Work is ongoing to provide injection of femto-second bunches with femto-second timing accuracy, for example by the so-called colliding pulse injector [20]. The work on channel guiding for laser beams aims at ultimately guiding lasers over the one meter scale, enabling laser wakefield acceleration over 1 m instead of 1 mm. A potential energy gain of 20 GeV in one meter seems possible if guiding can be achieved over this length [21]. Laser guiding with plasma fibers [22, 23, 24] and thin capillary tubes [25] is under study.

Beam induced wakefields The situation is qualitatively different if the plasma wakefield is induced by a high energy electron bunch. This beam has enough stiffness to easily traverse many meters of plasma and also allows detailed studies of the beam dynamics in long plasmas. Electron beams with high energy, low emittance, and short length are available at several accelerator laboratories. At SLAC a series of plasma wakefield acceleration experiments (E-157, E-162, E-164) utilizes the 30 GeV, 0.6 mm long electron bunches at the end of the SLAC linac [26, 10, 27, 28]. The beam is sent into a 1.4 m long plasma. However, the bunches are not short enough to easily fit with the mm plasma wavelength. This constrains the plasma density to low values and therefore lower accelerating gradients.

The SLAC experiments utilize a single electron or positron bunch to both induce (head) and witness (tail) the plasma wakefields. The head and the core of the bunch is decelerated while the tail is accelerated. Published results report on the transverse beam dynamics of the electron beam [29], on x-ray emission due to particle oscillation in the strong focusing field [30], on collective refraction of the electron beam at the plasma-gas boundary [31, 32], and on radiation measurements [33]. Experimental data on transverse focusing effects is shown in Fig. 4 from the SLAC E-157 experiment [31, 32]. The good agreement with the expected behavior is noted.

Improved data on electron acceleration in the 1.4 m long plasma has been collected during the SLAC E-162 experiment. It has been analyzed. Acceleration and deceleration data has been reported but not yet published, so that results are not included here. Maximum energy loss and gain of 100-200 MeV over the 1.4 m is predicted. The published results show the good potential of long plasmas for accelerators. Long plasmas cannot only be used as accelerat-

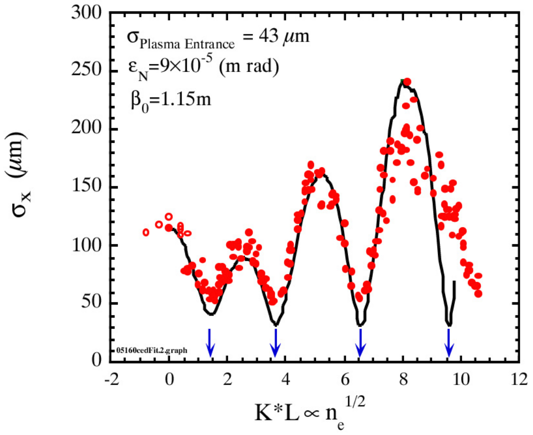

Figure 4: Horizontal beam size downstream of a 1.4 m long plasma versus integrated phase advance in the plasma (which is proportional to the square root of plasma density n_e). The focusing force modulates the size and divergence of the unmatched beam at the plasma exit. The solid line indicates the expected behavior. From [32].

ing structures, but also as strong wigglers, kickers, spoilers, lenses, . . .

The further progress for beam-driven plasma wakefield accelerators depends on the availability of shorter bunches, which however become more and more available. For example, the SLAC experiment E-164 will use SLAC linac bunches compressed by a factor 6 to about 100 μm to achieve an accelerating gradient of up to 20 GV/m over a plasma length of 30 cm. At the same time higher density plasmas must be generated and controlled.

5 USAGE IN A LINEAR COLLIDER

The basic requirements beyond a next generation e^+e^- linear collider are generally taken to include a 5 TeV center-of-mass energy (beam energy $E = 2.5$ TeV) and a luminosity L higher than 10^{35} cm^{-2}s^{-1}. Luminosity should increase as the square of the beam energy ($L \propto E^2$). The length L_{acc} of the accelerator is proportional to the beam energy divided by the accelerating gradient G. In order to keep the size of the accelerator complex reasonable the accelerating gradient must be as high as possible. Present RF technology in cold and warm metallic structures aims at using accelerating gradients between 35 MV/m and 150 MV/m [7, 8]. As discussed above, advanced acceleration techniques promise to advance this gradient by several orders of magnitude. However, this is not sufficient. In addition the technology must be efficient and preserve emittance.

The beam power P_b can be expressed as a function of beam energy E and luminosity L:

$$P_b = 4\pi \frac{\sigma_x^* \sigma_y^*}{N_e} EL \tag{4}$$

Here, σ_x^* and σ_y^* are the beam sizes at the interaction point and N_e is the bunch population. With a typical transverse IP cross section of (10 nm)^2 and a bunch population of 5×10^9 a beam power above 100 MW is obtained for the target energy and luminosity values listed above. It is seen that the accelerating fields must be generated and coupled to the beam very efficiently in order to keep power consumption reasonable. At the same time the normalized emittance must be preserved during beam acceleration, such that small IP spot sizes can be achieved.

Efficiency The advanced accelerator research is still in an early stage where the basic technologies are developed. Efficiency is not a priority and especially not yet optimized. However, the high available peak power and high available wall-plug-to-photon efficiencies (20-40%) of modern solid-state lasers [11] are encouraging. In addition ideas of matrix accelerators have the potential to further increase efficiencies. The efficiency for beam-driven plasma wakefield acceleration is estimated to be about 30% for the parameters of the SLAC experiment E-164.

Emittance preservation The strong transverse fields in the plasmas impose strict tolerances for the preservation of normalized emittance. Any linear collider must be made of many acceleration units. The center of the transverse focusing field in each unit is defined by the path of the driving particle bunch or laser pulse. The accelerated beam will in general have some offset with respect to this center and will therefore experience a dipole deflection. The resulting betatron oscillation will rapidly decohere and the emittance is diluted. The alignment tolerances have been estimated for basic examples of plasma-based 1 TeV colliders and were found to be 30-300 nm for a growth in normalized emittance from 4×10^{-8} m-rad to 12×10^{-8} m-rad [34]. This seems to be difficult. The solution to this problem would be the use of hollow plasma channels [34]. The accelerated beam would be transported through an empty channel such that no focusing fields are experienced. The surrounding plasma will still induce longitudinal fields that can be used for acceleration. Simulations predict that appropriate solutions can be found for both electron and positron beams [35].

A plasma afterburner as a first step? Accelerator laboratories have always greatly benefited from combining their existing accelerator facilities with upgrades or extensions. This maximizes the use of past investments and minimizes the cost of the new facilities. In this view it has been proposed to extend the existing 2×50 GeV Stanford Linear Collider (SLC) into a roughly 2×100 GeV collider. This would be achieved by installing two 7 m long plasma acceleration units (”plasma afterburners”) with a gradient of 7 GV/m just around the interaction point [36]. The SLC arcs are used in this scheme for bunch compression and separate drive and witness bunches would be employed. The final focusing could be done with plasma lenses. Though many important problems of such a scheme remain to be addressed, the scope of such a test facility seems manageable and could provide the first important step towards a plasma-based linear collider. If the energy reach could be extended to the Higgs, such a facility could even support important particle physics studies.

6 CONCLUSION AND OUTLOOK

The field of advanced accelerator research has seen important progress over the last years. Experiments have demonstrated plasma-based laser wakefield acceleration with gradients of up to 160 GV/m, however, only over mm lengths. The work on dedicated femto-second injectors and guiding of the laser beams should allow to significantly advance the acceleration length in the coming years. It is hoped that a 20 GeV beam acceleration can be achieved in a 1 m length.

Beam-driven plasma experiments are presently constrained to lower plasma densities and have tested acceleration in the 150 MV/m range over 1.4 m. The detailed studies of beam-plasma interaction over 1.4 m have yielded fascinating results with possible new accelerator applications for plasmas (plasma kicker, transverse beam dynamics, plasma wiggler,…). An future experiment will use shorter electron bunches and higher plasma densities to test accelerating gradients of up to 20 GV/m over 30 cm. A 2×15 m long plasma afterburner for the Stanford Linear Collider (SLC) could offer the first possibility to use plasma acceleration for particle physics. This idea aims at boosting the SLC collision energy from 90 GeV to around 200 GeV center-of-mass. For large plasma-based linacs, both laser- and beam-driven, important problems of emittance preservation are expected and remain to be addressed, possibly with hollow plasma channels.

Non-plasma based acceleration schemes open additional perspectives for future accelerators. The idea of an ”accelerator on a chip” with dielectric structures seems intriguing. The laser power source, power transmission system, accelerator structures and beam diagnostics would be lithographically produced on a single substrate by using semiconductor processes. The high power and good efficiency of modern lasers is encouraging for these studies.

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